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AN INTRODUCTION TO THE HELICOPTER

By Alexander Klemin

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AN INTRODUCTION TO THE HELICOPTER.

By Alexander Klemin.*

The helicopter or direct-lift type of aircraft has many enthusiastic supporters, and the achievement of vertical ascent, vertical descent, and hovering are beyond doubt of real interest. In spite of numerous flights already made with this type of aircraft, it is difficult to say at the moment whether we have, in the present-day helicopter, the first stages of a valuable type of flying machine, or merely a forced idea. There is, however, a possibility of ultimate success, and investigation should undoubtedly be continued till a definite solution is reached.

It is the object of this report to review briefly the aerodynamic and construction data already available and to set forth the difficulties which must be met.

To achieve utility, the helicopter must climb vertically with a moderate degree of useful load; attain a reasonable ceiling; achieve vertical descent with engines in action; achieve safe descent - if not vertically, then at least on a steep path with dead engine; have a reasonable speed in horizontal flight; be fairly stable and completely controllable;

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and have reasonable assurance of correct functioning of its mechanism. In these requirements we have the outline of the whole subject.

Notation

D = diameter of an airscrew, ft.

A = disk area or area swept out by blades of an airscrew, sq. ft.

n = r.p.s.

V = velocity, ft. per sec.

ρ = 0.00237 = absolute density of standard air per cu.ft.

T = thrust of an airscrew, lb.

T_c = thrust coefficient, such that $T = T_c n^2 D^4$

Q = torque of an airscrew, ft.-lb.

Q_c = torque coefficient, such that $Q = Q_c n^2 D^5$

P = work in ft.-lb. imparted to an airscrew per sec.

P_c = power coefficient, such that $P = P_c n^3 D^5$

K_f = ratio between actual lift secured from an airscrew, and theoretical lift on the Froude momentum theory $= \dfrac{0.1273 T_c^{3/2}}{Q_c}$

R = aerodynamic resistance in lb.

K = coefficient of resistance, referred to the disk area of an airscrew, such that $R = K\,AV^2$, when the disk is perpendicular to the line of motion.

K_L = coefficient of lift, referred to the disk area of an airscrew, such that the force perpendicular to the line of motion $L = K_L AV^2$

K_D = coefficient of drag, referred to the disk area of an airscrew, such that the force along the line of motion $D = K_D AV^2$.

i = angle of incidence to the flight path of the plane of rotation of an airscrew.

θ = angle of glide in oblique descent.

I. Lifting Airscrews

Obtaining a large thrust/power ratio with a lifting airscrew is not the solution of the helicopter, and is in fact one of the requirements most readily achieved. Without going into the detail design of the lifting airscrew, we shall investigate the theoretical limit of this ratio, and see how closely it has been approached in actual design.

Thrust/Power Ratio in a Perfect Fluid. Froude's momentum theory may be readily applied for a perfect fluid, that is, one in which the blades offer no aerodynamic resistance. The fundamental conception is that the air above the hovering airscrew ~~starts~~ from rest, approaches it with a velocity V_1 in a stream equal in area to that of the circular disk swept out by the blades, and below the airscrew passes on with a greater velocity V_2 in a contracted stream as shown in Fig. 1. The mass of air dealt with by the airscrew per unit of time is $\rho \frac{\pi D^2}{4} V_1$, and since the final velocity is V_2, the thrust

$$T = \rho \frac{\pi D^2}{4} V_1 V_2$$

The work done by the airscrew on the air is $T V_1$ and is equal to the kinetic energy of the air in the contracted stream (since there are no aerodynamic losses). Therefore, the power expended

$$P = TV_1 = \rho \frac{\pi D^2}{4} V_1{}^2 V_2 = \rho \frac{\pi D^2}{4} V_1 \frac{V_2{}^2}{2}$$

It follows that $V_1 = \frac{V_2}{2}$, and also that $\frac{T}{P} = \frac{1}{V_1} = \frac{2}{V_2}$. From this we see that the thrust/power ratio increases as the velocity of the air driven through the propeller decreases. Also, the greater the diameter and disk area, the less the air velocity and the greater the value of thrust/power.

$$\text{If} \quad A = \frac{\pi D^2}{4}, \ \frac{1}{V} = \sqrt{\rho \frac{\pi D^2}{4} \frac{2}{T}} = \sqrt{2 \rho} \frac{1}{\sqrt{T/A}}$$

and

$$\frac{T}{P} = \sqrt{2 \rho} \frac{1}{\sqrt{T/A}},$$

a mathematical expression indicating that the thrust/power ratio varies inversely as the square root of the thrust loading/disk area.

Correction Factor for an Imperfect Fluid. The theoretical value of T/P can never be attained. To determine the value of any lifting airscrew, we must find the value of a correcting factor K_f such that

$$\frac{T}{P} = K_f \sqrt{2 \rho} \frac{1}{\sqrt{T/A}}$$

K_f depending on the aerodynamic characteristics of the propeller.

Characteristics of Geometrically Similar Propellers. For geometrically similar propellers, K_f is a constant, and determines fully the "efficiency" of the airscrew. It is some-times more convenient to use the following relationships, however:

$$T = T_c n^2 D^4$$

$$Q = Q_c n^2 D^5$$

$$P = P_c n^3 D^5$$

where T and T_c are thrust and thrust coefficient, respectively; Q and Q_c, torque and torque coefficient; P and P_c, power and power coefficient; and n, r.p.s.

It follows that

$$\frac{T}{P} \propto \frac{1}{nD}$$

This relationship indicates that the tip speed (π ND) should be as low as possible to give a high value of T/P. For a constant thrust $D = \sqrt[4]{\frac{T}{T_c \rho n^2}}$, so that if n is decreased, D decreases proportionately less, and the product nD decreases. Hence it is advantageous to decrease n and increase D as far as practicable, a conclusion agreeing with the Froude momentum theory.

<u>Comparison of Different Types of Propellers</u>. For a helicopter airscrew it is desirable that for a given thrust and power, the diameter be as small as possible; that to keep down gear-reduction ratios, n be as high as possible; and that to keep down centrifugal effects, n be small. These are somewhat conflicting requirements. Also other considerations enter such as characteristics of the airscrew in climb, descent, and forward

flight. But in the preliminary selection of an airscrew T/P for any given disk loading, the value of K_f is the readiest basis of comparison.

Since experimental results are generally given in terms of T_c and Q_c, it is convenient to relate K_f with them. It can be shown that

$$K_f = \frac{T_c^{3/2}}{Q_c \pi^{3/2} \sqrt{2}} = \frac{0.1273\ T_c^{3/2}}{Q_c}$$

and this relationship shows that the value of T_c/Q_c is not a sufficient criterion.

Some Experimental Results. An enormous amount of experimental work has been done on airscrews working at a fixed point, with every kind of blade form, pitch, etc. Characteristics of a few representative propellers are given in Table I to indicate what the values of K_f, T_c and Q_c are at the present time.

Table I. Characteristics of Some Lifting Propellers.

Authority	Description of Propeller	T_c	Q_c	K_f
A. Fage & H.E. Collins, N. P. L.	Four-bladed, flat undersurface, chords of blade sections parallel to each other, plan form widening toward the tip, angle of blade 9.75 deg. Pitch diameter ratio 0.49.	0.08640	0.00600	0.536
A. Fage & H.E. Collins, NPL.	Two-bladed propeller, similar to above, angle of blade 12.55 deg.	0.07200	0.00526	0.517
W.F.Durand & E.P.Lesley,NACA.	Propeller No.5, two-bladed pitch ratio 0.9, mean blade width 0.2 r	0.15100	0.01105	0.680

Table I. Characteristics of Some Lifting Propellers (Cont.)

Authority	Description of Propeller	T_c	Q_c	K_f
W.F.Durand & E.P.Lesley, NACA.	Propeller No.44, two-bladed pitch ratio 0.7, mean blade width 0.27.	0.16700	0.01180	0.740

It is remarkable how near to the theoretical lift, the Durand & Lesley Propeller No. 44 approaches, although it was not designed for helicopter use. In the curve of Fig. 2, for Durand 44 and constant 100 HP., lift in pounds is plotted against diameter. Disregarding the weight of the airscrew itself, it is clear that any desired lift can be readily achieved with a given horsepower, if the size of the airscrews is not limited, and if adequate gear reduction is introduced between the high-speed engine and the airscrews, which must be slow to be efficient.

Tandem Airscrews. No very reliable data are available for tandem airscrews. In some of Klingenberg's experiments* a screw of 8 m diameter gave 200 kg (440 lb.) lift with 34 HP.; a screw of 6 m diameter gave 200 kg lift with 42 HP.; the combination of the two in tandem, with the smaller airscrew placed in the contracted airstream of the larger airscrew, gave a lift of 430 kg with only 69 HP.

II. Climb

The helicopter airscrew must do more than provide lift; it

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* "Zeitschrift des Vereines deutscher Ingenieure," 1910, p.1009.

must be capable of giving reasonable climb and ceiling. The regime of the helicopter airscrew in vertical climb coincides with that of an airplane propeller working at a very low value of forward velocity. It does not follow that the airscrew which gives the highest lift for a given horsepower and diameter, will always be the best for climb - its properties for various values of V/nD must be studied. There is no doubt also that a variable-pitch airscrew would be needed in achieving the best results. Another question to be studied is whether vertical or oblique climb is likely to be most effective.

A Calculation for Vertical Climb. One of the propellers studied by A. Fage and H. E. Collins is sufficiently typical for an illustrative calculation. This is a four-bladed propeller with a constant blade angle of 9.9 deg. Its characteristics are as given in Table II.

Table II. Characteristics of Typical Four-Bladed Propeller.

	$\frac{V}{nD}$	T_c	Q_c	$\left(\frac{\text{Thrust in lb.}}{\text{Horsepower}} \times Dn\right)$
	-0.204	0.1010	0.00720	1,230
	-0.182	0.1040	0.00726	1,250
Descent	-0.159	0.1050	0.00757	1,215
	-0.130	0.1070	0.00736	1,270
	-0.087	0.1075	0.00765	1,230
	-0.061	0.1080	0.00759	1,240
Hovering	0	0.1015	0.00743	1,190
	+0.082	0.0930	0.00684	1,190
	+0.135	0.0848	0.00650	1,140
Climb	+0.269	0.0563	0.00525	940
	+0.289	0.0538	0.00493	955
	+0.301	0.0485	0.00479	885

If employed on a 2000-pound helicopter, 100 HP. would be sufficient to sustain this machine with $n = 1.23$ r.p.s., $D = 48.4$ ft., and $Q = 7150$ ft.-lb. (neglecting all gear losses).

Suppose it is required to secure an initial climb of 10 ft. per sec., or 600 ft. per min. The resistance of the rest of the helicopter to vertical motion may be neglected at this low speed, and the thrust then remains constant at 2000 lb. No exact mathematical solution is possible, but a ready method of calculation is obtained by assuming values of n greater than 1.23 - since with constant thrust and positive values of V/nD, T_c diminishes and n must increase. When $n = 1.4$, $V/nD = 0.147$. By interpolation from Table II, $(T/P)\ Dn = 1100$ and $T/P = 16.3$, so that 123 HP. is required, and a torque of 7700 ft.-lb. If no variable-speed reduction is included in the transmission system, this means that the engine would have to deliver the 100 HP. required for sustentation, throttled down to some extent. If the maximum horsepower employed were about 150 HP., there would not be the slightest difficulty in meeting this condition. Provided always that in a helicopter the maximum horsepower is not designed to give mere sustentation, there is apparently no difficulty in securing adequate vertical climb. In vertical climb the helicopter has the inherent advantage over the airplane that it has no great aerodynamic resistance to overcome - the power goes directly into work against gravity.

Ceiling. Since the lift or thrust in hovering flight at ceiling is the same as at ground level, and $T = \rho\ T_c\ n^2\ D^4$, $\rho\ n^2$ = a constant = C, and $n = \frac{C}{\sqrt{\rho}}$. And since $P = \rho\ P_c\ n^3\ D^5 = \rho\ P_c \frac{C^3}{\rho^{3/2}} D^5 = \frac{P_c C^3 D^5}{\sqrt{\rho}}$, the power required to maintain hovering flight varies inversely as the square root of the density. For an airplane, minimum power at same altitude likewise varies inversely as the square root of the density. As a first approximation it may be assumed, therefore, that if the ratio (available horsepower/minimum power required at ground) of the airplane is equal to the ratio (available horsepower/minimum power required at ground) of the helicopter, the ceilings of the two types of aircraft will be approximately the same, though in all probability the helicopter will reach its ceiling far more quickly.

Oblique Climb. It has been found in a number of laboratories that when an airscrew is working in a side wind, the coefficient of thrust increases, while the coefficient of torque diminishes as compared with the torque and thrust coefficients *au point fixe*.

For example, in Durand and Lesley's experiments* on propellers in yaw, the figures given in Table III obtain for propeller No. 5.

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* "Tests on Air Propellers in Yaw," W. F. Durand and E. P. Lesley, National Advisory Committee for Aeronautics.

Table III. Air Propellers in Yaw.

$\frac{V}{nD}$	Angle of yaw	T_c	Q_c	Ratio of power for same thrust as at V/nD=0, yaw = 90 deg.
0	90 deg.	0.151	0.01105	1.0
0.373	90 "	0.151	0.01050	0.942
1.91	90 "	0.261	0.01495	0.762
0.372	85 "	0.1611	0.01122	0.925
1.58	85 "	0.2145	0.01500	0.785

It is seen that the power required diminishes considerably in the side wind at high values of V/nD. For 85 deg. yaw there is in addition the advantage of a forward component of the thrust. The same effects persist with larger angles of yaw. From experiments such as these, a number of writers have concluded that a helicopter could lift itself from the ground with less power in a side wind and also climb better on an oblique path, with the plane of rotation at a negative angle to the flight path.

But Durand and Lesley specifically state that they were not in a position to measure the forces perpendicular to the axis of rotation which must inevitably arise in a side wind. Riabouchinsky has fortunately made some tests in side winds, with angle of incidence of the plane of rotation held at zero, however, in which the lateral component was measured.

Some illustrative results are taken from these tests* and given in Table IV for a small airscrew of 25 cm (10 in.) diameter.

* Institut Aerodynamique de Koutchino, Table II.

Table IV. Data of Test of a 10-inch Airscrew.

$\frac{V}{nD}$	V m per sec.	n, r.p.s.	T kg	P, work in kg-m	R, Lateral resistance kg	RV, work required to overcome lateral resistance	Total work P + RV, kg-m
0	0	20.0	0.0240	0.0740	0	0	0.07400
0.726	3	16.5	0.0240	0.0640	0.00250	0.00750	0.07150
0	0	11.6	0.0081	0.0162	0	0	0.01620
3.020	6	7.9	0.0081	0.0139	0.00410	0.02466	0.03856

While Riabouchinsky's experiments were conducted on inefficient propellers, nevertheless the approximate conclusion may be drawn that less total power is required in a side wind only at small values of V/nD. With large values of V/nD the lateral resistance becomes large enough to offset the apparently advantageous effect of the side wind.

Granted even that a helicopter could get off the ground with a little less power, if it started off with some lateral velocity, the author sees no particular advantage in this. A helicopter which has so little reserve power as to necessitate such a maneuver to get off, would be useless.

It is possible also that by making a get-away at a high lateral speed, the diameter of the airscrews might be somewhat reduced because of the higher thrust coefficients. But in that case we would be departing from the fundamental advantages of the helicopter, and devising an inefficient equivalent of the airplane.

For much the same reasons the author sees no possibility of securing better climb by flying on an oblique path of moderate steepness. Particularly, since with the helicopter climbing on an oblique path the parasite resistance of the craft would be much greater than in vertical ascent. It is just possible that better climb might be secured by rising on a very steep path than by vertical ascent, but this seems contrary to the "instinct of mechanics."

III. Vertical Descent with Dead Engine

Limit for Speed in Vertical Descent. The limit of speed will be fixed by (1) physiological considerations, (2) by the factor of safety of the helicopter structure, and (3) by the character of the shock-absorbing mechanism. Damblanc* estimates the possible limit as 5 m (16.4 ft.) per sec. This seems large until it is considered that this corresponds to a vertical fall under gravity of only a little over 4 ft. Pilots in airplanes seem to be able to stand violent accelerations with ease, and with careful design of the shock-absorbing system it should be permissible to design for a vertical velocity of some 16 ft. per sec.

Theoretical Limits of Resistance Coefficients in Vertical Descent. If the Newtonian hypothesis were admissible, and particles of air striking a disk perpendicular to the wind were

* "The Problem of the Helicopter," L. Damblanc, Aeronautical Journal, January, 1921.

deflected at right angles to their original path, then the resistance of the disk would be ρAV^2. Hence in the equation $R = K\rho AV^2$, K would be equal to 1. This is evidently the maximum value which could ever be secured for K. But the air meeting a disk separates and flows past it, and the resistance coefficient has only a value of 0.6. The resistance coefficient of a parachute is approximately 0.7 based on its projected area, and the parachute approximates a hollow hemisphere, and evidently captures the air very effectively.

It seems difficult to conceive of any airscrew or windmill exceeding or even approaching this value of 0.7. It is useful to examine the resistance of a windmill - which for our purposes may be termed an airbrake - on the basis of Froude's momentum theory.* In Fig. 3 the column of air is conceived as approaching the airscrew with a velocity V in a stream somewhat narrower than the disk diameter, reaching the screw with a velocity V_1, receiving an instantaneous increase in pressure, and finally resuming the initial pressure at a smaller velocity V_2. From considerations of momentum

$$T = \rho \frac{\pi D^2}{4} V_1 \ (V - V_2)$$

Assuming Bernoulli's equation to hold from A to B, and from B to C, the pressures on the two sides of the airscrew disk will be $p + \rho \frac{V^2}{2} - \rho \frac{V_1^2}{2}$ and $p + \rho \frac{V_2^2}{2} - \rho \frac{V_1^2}{2}$. Hence $T = \rho \frac{\pi D^2}{4} (V^2 - V_2^2)$. Equating the two expressions for T, it

* Theoretische Bemerkungen zur Frage des Schraubenfliegers, Th. v. Karman, "Zeitschrift fur Flugtechnik," December 31, 1921.

is found that $V_1 = \frac{V + V_2}{2}$, (also that $V_1 - V_2 = \frac{V - V_2}{2}$, so that decrease in velocity of the air column before it reaches the airscrew is equal to subsequent decrease). Eliminating V_1 in the first expression for T, it is found that

$T = \rho \frac{\pi D^2}{4} \left(\frac{V^2 - V_2^2}{2}\right)$: If $V_2 = 0$, $T = \rho \frac{\pi D^2}{4} \frac{V^2}{2}$ or $K = 0.5$.

K seems very small, particularly as frictional losses are here neglected, and in actual experiments this value of K has been exceeded. Probably this is due to the fact that while the column of air before the disk is considered as narrower than the disk diameter, in reality an air stream of greater diameter may be affected. Also in the Froude momentum theory the whole mass of air affected is considered as passing through the disk while in reality some of it may flow round the edges as in the case of a flat plate. Also, the theory does not take in the possibility of rotational motion being imparted to the air. Applications of the vortex theory will bring theoretical and experimental values closer together. The Froude momentum theory does indicate, however, that even skilled design of airbrakes will not give very much higher values of K than 0.5.

Even if a coefficient of 0.6, equal to that of a flat plate, is secured, helicopter diameters remain extremely large for reasonable terminal velocity in vertical descent. Thus for a 2000-pound helicopter, if $K = 0.6$, $V = 16$, and $\rho = 0.00237$, then $D = 83.5$ ft. diameter; or if two airscrews are employed, each one must have a diameter of 59.4 ft.

Tandem airscrews are likely to be a very poor combination for vertical descent. Eiffel* has shown that two flat plates perpendicular to the airstream and in tandem may have a combined resistance of less than that of one plate (the rear disk, under the action of the suction of the forward disk may actually experience a negative resistance), and the same result is likely to occur for a tandem airscrew brake.

In a tandem airbrake, if the lower screw of the combination retards the column of air efficiently, there is little energy left to act upon the upper airscrew. If V_2 is the velocity of the air when it reaches the upper screw, its thrust on the Froude momentum theory will be given by the expression $T = \rho \frac{\pi D^2}{4} \left(\frac{V_2^2 - V_3^2}{2}\right)$, where V_3 is the final velocity after passing through the second airscrew. Hence the total thrust of the combination will be $\rho \frac{\pi D^2}{4} \left(\frac{V^2 - V_2^2}{2}\right) + \rho \frac{\pi D^2}{4} \frac{V_2^2 - V_3^2}{2}$ and can never exceed $\rho \frac{\pi D^2}{4} \frac{V^2}{2}$ or give a resistance coefficient greater than 0.5.

<u>Resistance Coefficients of Normal Airscrews in Vertical Descent</u>. Supporters of the helicopter have maintained that normal lifting airscrews would give sufficient parachutal effect in vertical descent without power. This is not substantiated by experimental values. There are three conditions to be considered: (a) when the airscrew is held, (b) when it is rotating as a windmill in a positive or normal direction, and (c) when it is rotating as a windmill in a negative direction.

* "The Resistance of Air and Aviation," G. Eiffel, translated by J. C. Hunsaker, pp. 55-60.

On vertical descent, an airscrew is not likely to act as a windmill rotating in a positive direction, unless it has a very low pitch, but condition (c) is likely to be realized at certain values of V/nD. Condition (c) is illustrated in Fig. 4.

On theoretical grounds, no very large resistance coefficient can be expected from either condition (a) or condition (b). Under condition (a) we simply have the resistance to forward motion of stationary blades, whose combined area is only a fraction of the disk area of the airscrew. Under condition (b) we may expect better values, but unfortunately the air now meets the rear edge instead of the forward edge of the airfoil blade element.

Some experimental results for various conditions of working are given in Tables V, VI, and VII.

Table V. Drag Coefficients of Normal Fixed Airscrews.

Designation of airscrew	Authority	Surface into the wind	Drag coefficient K referred to disk area of airscrew
4-bladed normal airscrew, pitch/diameter ratio 0.7	C.N.H. Lock & H. Bateman N. P. L.	Upper	0.074
4-bladed airscrew "A," blade angle 2° (Windmill)	Lock & Bateman	Under	0.099
2-bladed airscrew "B," blade angle ½° (Windmill)	Lock & Bateman	Under	0.063
2-bladed airscrew, relative pitch 0.4	W. Margoulis	Upper Under	0.0442 0.0535
2-bladed airscrew, relative pitch 0.8	W. Margoulis	Upper Under	0.0465 0.0610

These results indicate quite clearly that the parachutal effect of the fixed helicopter airscrew in vertical descent would be negligible in practice. The values for fixed airscrews with the upper surface into the wind are given merely for comparison.

Table VI. Normal Airscrews in Vertical Descent Turning Freely as Windmills with no Torque.

Designation of airscrew	Authority	Direction of rotation (Positive is normal)	$\frac{V}{nD}$	Drag coefficient referred to entire disk area
2-bladed airscrew No.1, relative pitch 0.4	W. Margoulis	negative	0.3	0.1130
2-bladed airscrew No.2, relative pitch 0.8	W. Margoulis	negative	0.55	0.123
2-bladed airscrew No.2, relative pitch 1.2	W. Margoulis	negative	0.93	0.0167

Table VII. Three Margoulis Airscrews, Relative Pitch 0.4 0.8, and 1.2, in Vertical Descent as Windmills, with Some Torque Effect.

No.1		No.2		No.3	
v/nD	Drag coefficient	V/nD	Drag coefficient	V/nD	Drag coefficient referred to disk area
0.3	0.1130	0.55	0.123	0.93	0.0167
0.4	0.2560	0.60	0.131	1.00	0.02460
0.5	0.288	0.70	0.124	1.10	0.0417
0.6	0.305	0.80	0.131	1.20	0.0550
0.7	0.278	0.90	0.135	1.5	0.0565
0.8	0.252	1.0	0.124		
1.0	0.200	1.1	0.116		
1.5	0.091	1.3	0.094		
		1.5	0.077		

From Tables VI and VII it is clear that a normal airscrew, acting as a windmill, will not exercise its maximum braking effeet when the torque is zero. Provided a torque is introduced, a low-pitch airscrew will develop quite an appreciable braking effect, approximately half that of the best drag coefficient obtained with specially designed windmill brakes. It might be possible to do better on descent with lower pitches and specially selected blade elements, but this would decrease lift efficiency; as it is, even with the highest value of the drag coefficient in Table VII, a diameter of 117.5 ft. would be required to give a speed of descent of 16 ft. per sec. for a 2000-pound airplane. The use of a normal airscrew without pitch variation does not seem a practical method of securing vertical descent.

Drag Coefficients of Specially Designed Windmills.- Fig. 5 indicates that with a negative blade setting an airscrew in vertical descent will rotate in a positive direction as a windmill, with the resultant wind striking the blade at an efficient angle. Accordingly the plan has often been suggested that the settings of the blades of the airscrew should be varied in vertical descent, and a number of experiments have been tried with windmills specially designed to give a large drag coefficient, but the only published results seem to be those of Lock and Bateman.*

The experiments were made on two normal airscrews "A" of two and four blades, of pitch diameter 0.3, in which the blades could be rotated, and a special windmill "B." In the airscrews

* Some Experiments on Airscrews at Zero Torque, with Applications to a Helicopter Descending with the Engine "off" and to the Design of Windmills. C. N. H. Lock and H. Bateman.

"A" the blade angle at 0.6 r from the center was taken as defining the blade angle, the normal blade angle at this point being 9 deg. In airscrew "B," which was specially designed as a brake-windmill, a pair of rectangular brass airfoils measuring $2\frac{1}{2}$ inches by 15 inches were attached by a pair of short brass spindles to the aluminum boss, thus making a two-bladed airscrew of diameter 3 ft., in which the chord, section and blade angle were constant along the blade, while the blade angle could be adjusted by rotating the blades. This gave a more suitable type of brake-windmill than "A" when rotated, and one of less peculiar shape. The results are summarized in Table VIII.

Table VIII. Experiments on Airscrews.

4-Bladed Airscrew "A" at Zero Torque.

Blade Angle setting* deg.	Rotation	V/nD	Drag coefficient referred to disk area	Remarks
-6	positive	0.504	0.422	--
-3	"	0.516	0.500	--
0	"	0.557	0.550	--
+2	negative	0.556	0.560	--
--	positive	0.618	0.562	--
--	negative	0.487	0.553	--
--	stopped	0	0.099	--

2-Bladed Airscrew "B" at Zero Torque.

Blade Angle setting* deg.	Rotation	V/nD	Drag coefficient referred to disk area	Remarks
-6	positive	0.294	0.387	--
-3	"	0.283	0.572	--
-1	"	0.323	0.592	--
$-\frac{1}{2}$	"	0.332	0.597	--
--	stopped	0	0.063	--

* At 0.6 r for airscrews "A."

Table VIII. Experiments on Airscrews (Cont.)

2-Bladed Airscrew "A," with Braking.

Blade Angle setting* deg.	Rotation	V/nD	Drag coefficient referred to disk area	Remarks
-6	Positive	0.406	0.338	Zero torque
--	"	0.450	0.343	Braking
--	"	0.487	0.342	Braking
0	"	0.409	0.537	Zero torque
--	"	0.432	0.526	Braking
--	"	0.508	0.421	Braking
--	Negative	0.407	0.540	Zero torque

*At 0.6 r for airscrews "A."

From these results it is evident that a two-bladed airscrew will answer quite as well as a four-bladed airscrew as far as drag coefficient in vertical descent is concerned. There is evidently no difficulty in securing a drag coefficient nearly that of a circular disk, namely, 0.6. Further, a drag coefficient of nearly this value can actually be secured with a small positive setting for the blade angles or very low pitch - in agreement with the Margoulis tests.

An important difference between these windmill tests and those of Margoulis on normal airscrews in vertical descent lies in the variation of drag with torque. For normal airscrews rotating in a negative direction on vertical descent, it appears to be necessary to introduce a braking torque on the airscrew shaft to secure high values of drag coefficient. For these windmills the drag coefficient seems to be almost independent of the braking torque - an important practical point, since it might thus be unnecessary to disconnect the dead engine when changing the angle of incidence.

The fact that K only varies slightly with the number of blades is in agreement with unpublished results of experiments in which a multiple-blade windmill was tried out.

Manipulation of the Airscrew to Decrease Rate of Vertical Descent. It has been suggested by a number of writers that by a process analogous to the flattening out of an airplane after a glide, the angle of the airscrew blade might also be manipulated on landing. On the descent, the blades would be rotated to a small negative angle with the plane of rotation so as to secure the maximum drag coefficient. Shortly before landing the pilot would place the blades at a positive angle to the plane of rotation, when the inertia of the airscrew would maintain rotation, and it would behave again as a lifting screw. This seems to be a very practical and promising suggestion, and if lifting airscrews are indeed provided with a variable-pitch mechanism, there is no reason why this maneuver should not be resorted to; if practical, the diameter of the airscrew could be cut down.

When an airplane engine stalls at get-away near the ground, the pilot may have but little time to bring his machine to a gliding attitude. If the helicopter engine stalls near the ground, the difficulty will be equally great. Reliable and very rapid control of the variable-pitch mechanism will be required. Clutches may also be necessary, so that the engine may be instantaneously disconnected when the airscrew is converted into a windmill, and zero torque is required to secure the greatest drag coefficient.

IV. Oblique Descent with Dead Engine

Since even with a specially designed brake-windmill only a drag coefficient of 0.6 is attainable, and large diameters are necessary in vertical descent, it is natural to examine the possibility of oblique descent, with the plane of rotation of the airscrew inclined to the flight path like the wing of an airplane on a glide, and the airscrew either fixed or rotating like a windmill in a side wind.

Oblique Descent with Fixed Airscrews. Margoulis experimented with the previously mentioned airscrew of pitch-diameter ratio 0.8. The airscrews were placed with the plane of rotation at 0, 15, 30, 60 and 90 degrees incidence to the flight path. The coefficients of lift and drag referred to the total disk area of the propeller were as given in Table IX. Since the forces on the airscrew vary with the exact position in which the airscrew is held, the values in Table IX are mean values of three different positions.

Table IX. Margoulis' Airscrew Experiments.

Incidence in deg.	0	15	30	60	90
K_L referred to disk area	0.00075	0.0206	0.0237	0.00134	0.0
K_D referred to disk area	0.02580	0.0330	0.0432	0.05860	0.0610
L/D	0.029	0.625	0.55	0.226	0.0

With such values the glide paths would always be exceedingly steep; and as a matter of fact, the lowest vertical component of velocity would be slightly greater than on direct vertical descent at 90 deg. incidence with airscrew fixed.

These unfavorable results might well have been expected; a fixed airscrew on a glide with its broken-up and unsymmetrically disposed surfaces could not possibly be as efficient as an ordinary wing surface of equal area. Also to seek improvement by reversing one of the blades on the glide would be futile.

Oblique Descent with Airscrew Rotating as a Windmill. With the same airscrew of pitch-diameter ratio 0.8, Margoulis experimented with the airscrew rotating as a windmill in oblique descent. In vertical descent $V = \sqrt{\frac{W}{\rho A}} \sqrt{\frac{1}{K_D}}$; in oblique descent the vertical component of velocity is given by the formula $\sqrt{\frac{W}{\rho A}} \sqrt{\frac{\cos\theta \sin^2\theta}{K_L}}$ $\sqrt{\frac{1}{K_D}}$ and $\sqrt{\frac{\cos\theta \sin^2\theta}{K_L}}$ are accordingly calculated in Table X.

Equilibrium, of course, is possible only where the torque is negative, so that a glide is not possible at either 0 or 15 deg. It is quite clear from Table X that the glide path in oblique descent would always be very steep with the airscrew in question, and that the least vertical velocity would be secured in vertical descent. It would seem from this that a descent on a gliding path with a normal airscrew would not be promising. It is therefore necessary to investigate oblique descent with a variable pitch airscrew.

Oblique Descent with a Windmill Type of Airscrew. No experiments are available for a windmill on oblique descent except those for La Cierva's Autogiro.*

Table X.

Angle of incidence	V/nD	K_D	K_L	Angle of glide θ deg.	$\sqrt{\frac{1}{K_D}}$	Torque (when positive power must be supplied by the engine)
90 deg.	1	0.1310	0	90.0	$\sqrt{7.63}$	negative
	2	0.0645	0	90.0	$\sqrt{15.5}$	"
	3	0.0600	0	90.0	$\sqrt{16.6}$	"
	4	0.0660	0	90.0	$\sqrt{15.15}$	"
					$\sqrt{\frac{\cos\theta\sin^2\theta}{K_L}}$	
60 deg.	1	0.11	0.0274	76.2	$\sqrt{8.2}$	negative
	2	0.0595	0.0246	67.6	$\sqrt{13.1}$	"
	3	0.0530	0.0218	67.5	$\sqrt{14.9}$	"
	4	0.0610	0.0192	72.6	$\sqrt{14.3}$	"
30 deg.	1	0.0760	−0.0486	---		positive
	2	0.0452	0.0	---	$22.1\left(=\sqrt{\frac{1}{K_D}}\right)$	"
	3	0.0435	0.0153	70.4	19.55	negative
	4	0.0447	0.0216	64.1	16.7	"

*Essais aerodynamiques d'un modele d'autogiro: J. De La Cierva, L"Aeronautique, April, 1934.

Table X (Cont.)

Angle of incidence	V/nD	K_D	K_L	Angle of glide, deg.	$\sqrt{\frac{\cos\theta\sin^2\theta}{K_L}}$	Torque (when positive power must be supplied by the engine
15 deg.	1	0.0430	-0.110	--		positive
	2	0.0318	-0.0252	--		"
	3	0.0304	-0.00238	--		"
	4	0.0336	+0.00925	74.6	26.6	"
	5	0.0330	+0.0169	62.9	21.6	"
					$\sqrt{\frac{1}{K_D}}$	
0 deg.	1	0.0274	-0.133		--	positive
	2	0.0218	-0.0374		--	"
	3	0.0218	-0.0152		--	"
	4	0.0256	-0.00595		--	"
	5	0.0254	0.0		39.6	"

A model of this, a four-bladed airscrew, Göttingen 429, in section for blade elements, with each blade at 2 deg. to the plane of rotation, diameter of airscrew 1.1 m (43.3 in.), width of blades 8 cm (3.15 in.), was tested with the plane of rotation at various angles of incidence to the forward wind, and the screw mounted freely in its bearings. The peculiarity of La Cierva's device is that each blade is flexibly connected to the axis of rotation, as shown in Fig. 6. Therefore, although but one airscrew is used, and the blade going into the wind meets a greater air velocity and experiences more lift, no banking effects are apparently produced in straight flight, the resultant force of each blade always passing through one point. The blade turning into the relative wind rises, however, until the centrifugal force, the weight of the blade, and the lift are all in equilibrium. The blades remain at the same angle of incidence to the plane of rotation during the peculiar feathering motion of the airscrew, but no doubt the rising of a blade tends to decrease its effective angle of incidence, and reduces the variation in lift. It is unfortunately impossible, in the scope of this report, to analyze the peculiar action of the blade and the varying aerodynamic conditions at each point on the path of rotation.

Even the action of an ordinary windmill, moving in a horizontal wind with its axis inclined to the path, is difficult to analyze, as indicated by the diagram of Fig. 7. Unlike a windmill rotating with its axis parallel to the line of motion, the windmill with its axis oblique to the motion may have its blades at one point of the circle tending to rotate in a positive direction, and at another point tending to rotate in a negative direction. If the torques on the windmill balance as a whole, so that the resultant torque is zero, the L/D of the whole windmill considered as a lifting surface will depend on the inclinations to the perpendicular to the flight path of the forces R in the diagrams of Fig. 7. It is conceivable that if the axis of rotation of the windmill is only at a slight inclination to the flight path, and the inclinations of R to the perpendicular to the flight path are alternately positive and negative, that a very high L/D for the whole disk surface might result - conceivably a higher L/D than that of a single blade element. The peculiar feathering action of the Autogiro may assist in securing this high L/D. Therefore it would be dangerous to dismiss as entirely impossible the surprising results obtained by La Cierva in the wind tunnel and given in Table XI.

Table XI. Wind Tunnel Tests of La Cierva's Autogiro.

Angle of incidence of plane of rotation to flight path deg.	L/D	K_L referred to entire disk area	K_D referred to entire disk area	Glide angle θ deg.	$\sqrt{\frac{\cos\theta \sin^2\theta}{K_L}}$
0	19.23	0.0386	0.00202	3	$\sqrt{0.069}$
1	27.78	0.0400	0.00144	2.05	$\sqrt{0.0296}$
2	20.00	0.0432	0.00216	2.8	$\sqrt{0.055}$
4	10.00	0.0535	0.00535	5.7	$\sqrt{0.181}$
6	6.06	0.0700	0.01150	9.4	$\sqrt{0.372}$
10	3.92	0.1130	0.02900	14.3	$\sqrt{0.524}$
16	2.77	0.2030	0.07400	20.1	$\sqrt{0.546}$
22	2.11	0.5500	0.26200	25.5	$\sqrt{0.308}$
26	1.85	0.7150	0.38700	28.4	$\sqrt{0.282}$
30	1.63	0.8050	0.49500	31.5	$\sqrt{0.244}$
34	1.53	1.1300	0.73600	33.2	$\sqrt{0.222}$

These figures indicate extraordinary possibilities for oblique descent with a skilfully designed windmill. Thus if the weight of the airplane is 2000 pounds, the angle of incidence 2 deg., the glide angle 2.8 deg., and the vertical component of velocity 16 ft. per sec., then from the formula

$$V \text{ (vertical)} = \sqrt{\frac{W}{\rho A}} \sqrt{\frac{\cos\theta \sin^2\theta}{K_L}},$$

we find that a windmill diameter of only 15.2 ft. would be required. If the steepest possible path were used, and the angle of incidence on the glide were 34 deg., a diameter of only 30.6 ft. would be required, and we would then have an airplane which could land in a horizontal attitude on the worst and smallest terrain, and come to rest almost immediately.

Of course, very great difficulties may be encountered in converting a normal lifting airscrew into a windmill by mechanical methods. The best plan form and blade-angle setting for the lifting airscrew might be far from the best for the windmill. The production of a compromise design will need very thorough aerodynamic research.

V. Forward Speed and Efficiency in Horizontal Flight

It has been shown by several investigators that for a given torque and R.P.M., the thrust along the airscrew axis increases with forward speed. From this it has been argued that a helicopter would be extremely efficient in forward speed. This is based on faulty analysis. The best method of approaching the problem is again to treat the airscrew as a lifting surface, and to consider work done in overcoming forward resistance, as well as the work done in imparting thrust to the airscrew.

Durand and Lesley's Experiments* at Zero Incidence for Plane of Rotation. A large number of propellers were tested by

* Tests on Air Propellers in Yaw, W. F. Durand and E. P. Lesley, National Advisory Committee for Aeronautics, Technical Report No. 113.

those investigators, with the axis of rotation at 90, 85, 80, 70, and 60 deg. to the relative wind, with the axis inclined, in all but the first case, in such a manner as to produce forward thrust coefficients along the axis, and torque coefficients were obtained; no allowance was made for lateral resistance.

It is convenient to introduce here an expression L/D_a for the lift/drag ratio of an airscrew working in a side wind. Where lateral resistance is neglected,

$$\frac{L}{D_a} = \frac{T}{\frac{(2\pi\ Qn)}{V}}$$

and since $T = T_c\ n^2\ D^4$ and $Q = Q_c\ n^2\ D^5$,

$$\frac{L}{D_a} = \frac{T_c}{Q_c}\ \frac{V}{2\pi\ nD} = \frac{T_c}{2\pi\ Q_c}\ \frac{V}{nD}$$

As a general rule it was found that the ratio T_c/Q_c increased considerably in going from small values of V/nD to the largest employed in the tests; for some propellers this ratio was more than doubled. Neglecting lateral resistance, the value of L/D_a would increase greatly with increasing values of V/nD. But it is impossible to imagine that T_c/Q_c would increase indefinitely with V/nD, and there are practical limitations to the value of V/nD in an actual helicopter. For our purpose, which is merely to approximate to values of forward efficiency <u>on a basis of insufficient experimental data</u>, it is sufficient to consider L/D_a for a few propellers at the highest V/nD tested.(see Table XII). Propellers of low pitch/diameter ratio seem to come off better, but the L/D_a values are poor even when the lateral resistance is neglected.

Table XII. Tests by Durand and Lesley on Propellers at 90 deg. Yaw or 0 deg. Incidence for Plane of Rotation.

Propeller	Pitch diameter ratio	Highest V/nD tested	T_c	Q_c	L/D	$\frac{(L/D_a)}{V/nD}$
5	0.7	1.190	0.2610	0.01945	4.07	2.13
9	0.5	1.301	0.1842	0.00779	4.90	3.76
139	0.3	0.423	0.0936	0.00346	1.83	4.30
146	0.3	1.333	0.1540	0.00455	7.15	5.38

Relf's Experiments at Zero Incidence.* These experiments were likewise at 90 deg. yaw, or 0 deg. incidence for the plane of rotation, with a two-bladed 2-ft.-diameter propeller of 2 ft. pitch. Lateral resistance was not taken into account. Two representative results are given in Table XIII.

Table XIII. Relf's Experiments at 0 deg. Incidence.

Wind speed ft. per sec. V	R.P.M.	V/nD	Thrust T lb.	Horsepower	$\frac{L}{D_a} = \frac{T \times V}{HP. \times 550}$
20	750	0.8	1.0	0.032	1.13
40	760	1.6	1.22	0.036	2.45

Riabouchinsky's Experiments** at Zero Incidence. Riabouchinsky experimented with a small airscrew of only 25 cm (10 in.) diameter, and a pitch/diameter ratio of 0.75, at 0 deg. inci-

* Test of a Propeller with its Axis of Rotation at Right Angles to the Wind Direction, E. F. Relf, R&M 265.
** Bulletin de l'Institut Aerodynamique de Koutchino, No. 2, D. Riabouchinsky.

dence for the plane of rotation, and wind speeds of 3, 4, 5 and 6 m per sec. (9.85 - 19.7 ft. per sec.). In his experiments lateral resistance was taken into account. The results are given in the original units in Table XIV.

Table XIV. Riabouchinsky's Experiments at 0 deg. Incidence.

Wind speed m per sec. V	r.p.s. N	V/nD	Thrust kg T	Work put into airscrew shaft kg-m per sec.	Lateral resistance kg R	L/D_a neglecting lateral resistance $\frac{TV}{P}$	L/D_a taking lateral resistance into account $\frac{TV}{P-RV}$
3	8.6	1.39	0.0076	0.0112	0.00140	2.03	1.49
6	17.5	1.37	0.0307	0.0846	0.00663	2.18	1.48
6	7.9	3.20	0.0139	0.0139	0.00411	3.44	1.26

These results do not seem very promising for the efficiency of a helicopter when operating with plane rotation at zero angle of incidence, but they were not obtained from modern propellers. Riabouchinsky's experiments are interesting in showing the considerable value of the lateral resistance, particularly at high values of V/nD. They put us on guard against expecting high efficiencies in forward flight with the axis of rotation inclined so as to produce a component of thrust in the direction of flight.

Horizontal Flight with Plane of Rotation Inclined at a Negative Angle to the Flight Path. From the experiments just described, it would appear that only low efficiency can be secured in horizontal flight with the plane of rotation parallel to the flight path. If the propeller is working in yaw other than 90 deg., and the forward component of the thrust and the lateral resistance are both neglected, the expression for L/D_a becomes (where γ = angle of yaw) $\frac{T_c \sin\gamma}{Q_c\ 2\pi}\ \frac{V}{nD}$. We shall examine the value of this expression for the propeller 146 in Durand and Lesley's experiments (see Table XV).

Table XV.

γ Angle of yaw, deg.	$\cos\gamma$	Highest V/nD tested	T_c	Q_c	$L/D_a = \frac{T_c \sin\gamma}{Q_c\ 2\pi}\ \frac{V}{nD}$
90	1.0	1.333	0.1540	0.00455	7.15
85	0.9962	1.201	0.1240	0.00539	4.40
80	0.9848	1.267	0.0977	0.00496	3.90
70	0.9397	1.262	0.0339	0.00402	1.59
60	0.8660	0.959	0.00665	0.00372	2.34

If the forward component of the thurst is taken into account, the expression for L/D_a becomes

$$\frac{(T_c \sin\gamma)\ V}{Q_c\ 2\pi\ nD - T_c\ \cos\gamma\ V} = \frac{T_c \sin\gamma}{\frac{Q_c\ 2\pi}{V/nD} - T_c\ \cos\gamma}$$

values of which are given in Table XVI.

Table XVI.

Angle of yaw deg.	Highest V/nD tested	$\dfrac{T_c \sin\gamma}{\dfrac{Q_c\,2\pi}{V/nD} - T_c \cos\gamma} = L/D_a$
90	1.333	7.15
85	1.201	7.42
80	1.267	12.50
70	1.262	3.88

The expression L/D_a can be brought into definite comparison with L/D_w, which will be used to denote the L/D of an airplane wing.

Thus for an airplane we can write, if η is the efficiency of the propeller and R_p the parasite resistance,

$$P\eta = \frac{WV}{L/D_w} + R_p\,V \text{ and } L/D_w = \frac{WV}{P\eta - R_p\,V}$$

For the helicopter we can write

$$P = \frac{W}{(L/D_a)}\,V + R_p\,V \text{ and } L/D_a = \frac{WV}{P - R_p\,V}$$

For the same power P and weight W, in order to have the same velocities for airplane and helicopter, $\left(\frac{P\eta - R_pV}{W}\right) L/D_w$ must equal $\left(\frac{P - RV}{W}\right) L/D_a$, or $L/D_a = L/D_w\left[1 - \frac{(P - P\eta)}{P - R_pV}\right]$. In other words, L/D_a can be less than L/D_w to secure the same effect.

We can now get an idea of the probable effectiveness of the airscrew in forward flight.

There are two extreme cases: (1) where the lateral resistance of the airscrew balances its forward component; and (2) where the forward component is undiminished by lateral resistance. With a propeller such as the Durand 146, we can by inclining the airscrew secure an L/D_a certainly not less than 4.40, never much greater than 12.50. Certainly an L/D_a of between 8 and 9 can be expected.

It may also be safely concluded that higher efficiency would be secured in forward flight by using an inclined airscrew than by the use of an auxiliary propeller. At least the experimental values of L/D_a, neglecting lateral resistance, are much higher in the former case Compare 13.5 at 80 deg. yaw in Table XVI with 7.15 at 90 deg. yaw in Table XII. Also for the helicopter with the inclined airscrew producing forward thrust there is a decided advantage in the fact that

$$L/D_a = L/D_w \left[1 - \frac{P - P\eta}{P - R_p V} \right]$$

With an auxiliary propeller there would be efficiency losses of the usual type in the auxiliary propeller itself; and this advantage would disappear. Granted that an inclined airscrew is used, that the parasite resistance can be kept down, and that the diameter of the airscrew can be kept within reasonable dimensions, by windmill action on oblique descent, so as to have high values of V/nD, there is no reason to doubt that fair speeds could be secured with a helicopter satisfactory in other respects.

For example, if it were possible to build a helicopter weighing 2500 lb., with 200 HP., and an equivalent parasite resistance of 15 sq.ft. (more than that of the DH4 airplane), and to have $L/D_a = 8$, solution of the equation

$$L/D_a = \frac{WV}{P - R_p\ V}, \text{ or } 8 = \frac{2500\ V}{(200 \times 550) - 0.0450\ V^3}$$

would give approximately a speed of 115 ft. per sec. or 78.5 M.P.H.

Estimates of Efficiency by Margoulis and Case. Margoulis' views on airscrews, with no motive power supplied to the shaft from an external source, are based on careful experiments. His estimates for L/D for power-driven airscrews are based on a series of unsatisfactory approximations and interpolations from the results of various laboratories. He finds maximum L/D to be only 1.7, with $\gamma = 60$ deg., but this need not be seriously regarded. Case* has designed a number of propellers on the simple blade-element theory and calculated their efficiency, for an angle of 10 deg. between the flight path and the plane of rotation. With a four-bladed screw of pitch/diameter ratio 0.3, $V/nD = 20$, $D = 40$ ft., $n = 1.46$ r.p.s., he found an effective L/D_a of 6.7. By making the effective angle of incidence 5 deg. along the blade, when meeting the forward wind an L/D_a of approximately 9 is deducible from Mr. Case's calculations.

* Helicopters, John Case, Aeronautical Journal, October, 1922.

It is doubtful whether for the complicated and varying conditions under which the helicopter airscrews must work when inclined to the side wind, calculations based on the simple blade-element theory will give accurate results. But still these careful calculations are pleasingly in agreement with hypotheses based on experimental values.

The elementary blade-element conditions for various points in the revolution of the airscrew are very complicated. The design of an airscrew, to give the best results, would evidently be a difficult proposition. It is doubtful if the inclined helicopter airscrew can be made as efficient as the combination of propulsive screw and lifting wing of the airplane, but it must be considered that in the inclined-screw helicopter there is only one transformation of energy; in the airplane there are two such transformations.

VI. Stability and Control

Stability in Vertical Movement and Vertical Winds. This first problem in the stability of the helicopter involving stability in vertical movement and vertical winds, has been well treated by Fage.* In Fig. 8 are shown typical propeller characteristic curves plotted against V/nD. From this it follows that if a down gust hits a hovering helicopter, it will be in

* Some Experiments on Helicopters, A. Fage and H. E. Collins, British Advisory Committee for Aeronautics, R&M 331; Airscrews in Theory and Experiment, A. Fage.

the region of positive V/nD, and while the engine will speed up a little as Q_c diminishes, T_c will diminish more rapidly, the thrust will decrease, and the machine will descend. If the down gust ceases, the helicopter will work in a region of negative V/nD and the thrust will increase accordingly, equilibrium being rapidly restored. If an up gust strikes the helicopter, its airscrew will be working in a region of negative V/nD, and the thrust will increase accordingly. If the up gust is very violent, however, so that the negative V/nD is numerically large, the thrust coefficient will decrease and the machine may drop. (This is not unlike the behavior of an airplane in vertical gusts.) Also, if for some reason, the helicopter should descend rapidly, it may reach the condition of large negative V/nD and drop with increasing velocity. Evidently the pilot will have to watch his throttle very carefully in vertical maneuvers. But with an engine responding readily to the throttle or a variable-pitch propeller, nothing serious need be feared.

Dihedrals in the Helicopter. Karman (Figs. 16 and 17) has shown that a helicopter with two screws rotating in opposite directions and placed above the center of gravity is likely to be unstable, whether the screws are coaxial or side by side. But an airplane wing of itself is not stable, and it does not seem fair to demand that a helicopter should be stable without

* Loc. cit.

some special arrangement of the airscrews. It seems possible to secure stability either longitudinally or laterally by the use of dihedral angles between the planes of rotation of two airscrews. If the helicopter is slightly tilted for some reason or another, the resultant of the two thrusts will no longer be vertical: there will be a side component in the direction of the tilt and a lateral movement in that direction. But Duranr and Lesley* have shown that when airscrews are placed with their planes of rotation oblique to the wind, the coefficient of thrust becomes smaller than the coefficient of thrust when the plane of rotation was parallel to the wind. The inclined screw has its plane of rotation inclined to the lateral motion, and therefore has less thrust. A righting moment is introduced thereby. Dr. De Bothezat, in building his helicopter, had four lifting screws disposed with a longitudinal and lateral dihedral, and evidently had this property in mind. From unofficial reports it is clear that his machine was stable.

It might be possible to secure both lateral and longitudinal dihedrals by the use of only three lifting screws suitably arranged.

If two coaxial screws are used, it might be possible to secure the necessary dihedrals by the use of a third or auxiliary airscrew. Whether a dihedral effect in a single airscrew can be secured by placing the blades at an upward angle to the

* National Advisory Committee for Aeronautics, Report 113.

axis of rotation, is an open question.

Damping in the Helicopter. Dihedrals in the helicopter, just as in the airplane, give static righting moments, but damping will also be present, even if no dihedral is embodied in the design. If a helicopter is rolling in such fashion that one airscrew rises, it can be seen from the curves of Fig. 8 that its thrust diminishes; simultaneously the thrust of the other airscrew will increase. There should be, therefore, damping in either roll or pitch for both three-screw and two-screw helicopters. It is a question, however, whether a two-screw coaxial helicopter would provide damping.

Fins to Give Equivalent of the Dihedral. Since it is advisable to keep the number of lifting screws down to a minimum, the possibility of using fins immediately suggests itself. In rapid forward flight the use of fins should be effective; if two coaxial screws are employed, one vertical fin placed high above the center of gravity, with its plane parallel to the line of flight, would be an effective substitute for the lateral dihedral. A stabilizer placed at a negative dihedral to the plane of rotation of the lifting screws might be an equally good substitute for the longitudinal dihedral. These auxiliary surfaces in rapid forward flight would not have to be of unduly large proportions.

But in hovering flight and vertical ascent or descent such auxiliary surfaces would be almost useless. For instance, if we imagine the coaxial screw helicopter in vertical ascent, with a horizontally disposed stabilizer, to pitch slightly, the horizontal stabilizer would be scarcely affected by the slight pitch. Similar considerations would apply in regard to vertical fins used as a substitute for lateral dihedral. In vertical ascent or descent the problem is somewhat easier than for hovering, but even if placed in the slipstream the auxiliary surfaces would have to be enormous to be effective. In all probability, if dihedrals between the lifting screws are not present, reliance will be placed on skilled actuation of the controls.

Directional Stability. So-called "directional stability," more properly "weathercock stability" has to be considered for the helicopter just as for the airplane. In the airplane weathercock stability is readily secured by a preponderance of fin area aft of the center of gravity. Propellers, whether propulsive or airplane propellers or lifting airscrews, may be considered as fins. In rapid forward flight the fin action of the propellers, whether two or four lifting screws were used, would be concentrated approximately at the center of gravity, and comparatively little power would be required of a vertically disposed fin to obtain "weathercock stability." In hovering and vertical ascent or descent it would act far less powerfully, and reliance would probably have to be placed on auxiliary steering propellers, and manual control.

Stability a Subject for Research. The above treatment of stability is obviously superficial. It seems to the author that prior to the building of full-sized helicopters a great deal of theoretical analysis and wind-tunnel experimentation should be undertaken as regards stability. It seems ridiculous to expose helicopter pilots to great hazards in their first painful efforts, when with some patient wind-tunnel work a machine fairly stable under all conditions might readily be evolved.

Control. The question of helicopter control is one decided by practical rather than theoretical considerations. There seems no reason, however, why complete control under all circumstances should not be more readily secured than stability. For rapid forward flight the requirements are not unlike those of an airplane, and systems of control readily suggest themselves. For the ailerons can be substituted variation in pitch of the lifting airscrews on either side of the longitudinal axis, or else movable fins or plates placed in the slipstream of the propellers. In forward flight a vertical tail rudder would be just as effective as on the airplane. So would an elevator.

In hovering or vertical flight an auxiliary elevator airscrew with variable or even reversible pitch would seem to be necessary, as also a steering airscrew - or steering airscrews.

The question of control would seem to offer wide scope for inventiveness and mechanical skill. Perfectly realizable, helicopter control is always likely to be more complicated and less certain than that of an airplane. A duplicate system of controls - one for forward flight, one for hovering - might conceivably be necessary. Descriptions of machines which follow illustrate a number of practical forms of control.

VII. Some Modern Helicopters

Berliner Helicopter. An early form of the Berliner helicopter was described in Mechanical Engineering for September, 1922. It was of the simplest possible form, with a 200 HP. engine driving two moderate-sized lifting airscrews on either side of the fuselage. Lateral control was secured by the use of three movable fins under each of the propellers; and longitudinal control by a small variable-pitch propeller at the rear of the fuselage. A horizontal stabilizer and elevators and rudder identical with those of an airplane were provided. Successful short flights were achieved.

Quite obviously, Berliner was not satisfied with the safety of his craft in case of engine failure; and in his next design sought to provide the ability to glide by embodying wing surfaces in the structure. It now became a helicopter-airplane. Outline drawings and photographs of this machine are shown in Fig. 9.*

* Notizario di Aeronautica, No. 5, May, 1924. Elicotero Berliner Modificato

The Berliner helicopter is now provided with a conventionally trussed triplane wing surface and two lifting propellers, which latter also provide forward thrust on inclination of the entire craft. The transmission system is carefully enclosed within the wing surfaces and the interplane struts.

The system of control is complete. A slight warping of the wings can be produced by a special control, whereby the axis of the lifting propellers can be inclined at different angles to the line of flight on either side of the machine; so that a turning couple can be obtained. With the lifting propellers in motion, the pilot regulates a variable-pitch propeller placed at the tail end of the machine, so as to raise the tail from the ground. Under the action of the lifting propeller the helicopter leaves the ground. The rear propeller permits the further inclination of the axis of the lifting propeller until a forward component of the thrust is obtained, with resulting forward speed. Lateral equilibrium is maintained by a system of movable fins placed below the disk area of the propellers. It can be seen that the system of control is fully operative whether in forward flight or hovering flight or vertical movement.

If the lifting propellers become inoperative, either owing to damage or engine failure, the machine becomes a glider. On the glide, wind-tunnel experiments seem to indicate a best L/D of only 4. On the glide, warping of the wings takes care of lateral control; an ordinary rudder and elevator act in the usual manner.

The gross weight of the machine with pilot and fuel for a twenty-minute flight is about 1950 lb. The engine is a Bentley Rotary Model 2, air-cooled, providing 220 HP. at 1200 R.P.M. The lifting propellers turn at about 560 R.P.M. and have a diameter of 15 ft. The span of the wings is 38 ft. and the chord is approximately 1 ft. 11 in. The overall length is 20 ft. 6 in. and overall height about 6 ft. 8 in.

According to reports of the Italian Air Attaché in Washington, the machine makes only a fair getaway. The maneuverability seems satisfactory, and the aircraft responds well to the controls. In a moderate but irregular wind the oscillations appeared important. The Berliner helicopter is still in an experimental form, but it has definitely achieved vertical flight, and complete freedom of evolution. Its ability to glide is an important factor as regards safety. The maximum duration of flight achieved so far appears to be 1 min. 35 sec., and the highest altitude reached, 15 ft.

Pescara Helicopter. This is shown in Fig. 10. It has made some excellent flights. The apparatus carries two six-bladed biplane airscrews of 21 ft. diameter. The engine is a 120 HP. Le Rhone. Manouvering is effected by modifying the incidence of the blades at any one point in their revolution. No very reliable technical information is available. The control seems very incomplete, and Pescara himself has complained of this.

It is very interesting to read in a recent report of the French Section Technique d'Aeronautique, that this competent body places most reliance on the helicopter airplane. Pescara now seems to be working on a machine of this type, termed a "helicoplane." A somewhat sketchy description of this design is available:

This machine has upper and lower wings revolving in opposite directions. They are connected through gearing and clutches to a 300 HP. engine situated immediately back of the wings of the fuselage. This engine is also connected through a clutch through a pusher propeller mounted at the rear end of the fuselage. The pilot sits immediately forward of the wings. The radiator is located in the front end of the fuselage. The machine will weigh 850 kg empty, and 1250 kg fully loaded. Surface loading will be approximately 80 kg per sq.m. The main vertical drive shaft to the helicoplanes proper terminates in the landing-gear fork support, and the vertical drive-shaft housing alone forms the main support for the planes proper. Small counterbalancing ailerons are fitted at the extremities of the helicoplanes. Elevator, stabilizer, and rudder are mounted in conventional fashion. The tail skid is really an extra strut to the landing gear proper to keep the propeller away from ground interference. In order to glide to earth in case the engine stops, Pescara claims that by varying the pitch of these helicoplanes and allowing them to be free to move, they will revolve in opposite directions while gliding without power and thus increase the gliding distance appreciably.

De Bothezat Helicopter.* This interesting machine is illustrated in Fig. 11. It was first flown on October 19, 1922. On April 17, 1923, with Colonel Thurman H. Bane as pilot, a four-man flight was made, with three men hanging on to the machine. Between these two dates the helicopter has made over 50 flights - no descent with engine cut being attempted, however.

The De Bothezat helicopter, as illustrated in Fig. 11, is provided with four lifting screws, each of 26½ ft. diameter, four-bladed, with wide blades (5 ft. toward the tip), giving a total blade area of 900 sq.ft. Although each blade screw was designed for a lift of 1000 lb., dynamometer tests were conducted up to a thrust of 1500 lb.

The weight empty is 3400 lb., and a useful weight of 1000 lb. has been carried. The weight empty exceeded original estimates considerably, as all new types of aircraft are bound to do. When the helicopter is in operation, two-thirds of its weight is rotating and about one-third only is stationary. The overall length is 65 ft.; width, 65 ft.; height, 10 ft.

It has been equipped with the B.R. 2 stationary air-cooled engine developing 200 HP., a 9-cylinder 200 HP. Le Rhone rotary

* Aero Digest, July, 1923; Slip Stream, April, 1924; International Air Congress, London, 1923.

engine failing to give satisfaction.

A central frame member supports the engine and four outwardly extending structural arms, built up of duralumin and steel tubing. One of these arms contains the pilot's seat and each supports one of the lifting screws at its outer end.

The engine drives a main shaft and four jackshafts, to each of which is connected a turret driven through ring and center gearing. The engine also drives two 4-bladed propellers, of the reversible-pitch type, one being rotated at each side of the pilot and facing forward so as to give a forward thrust.

Unofficial reports indicate that the De Bothezat helicopter was moderately satisfactory in control and stability. In the four-man flight mentioned above, a man was hanging on at the extreme end of the rear arm with his weight totally unbalanced.

We have discussed in the previous section the utility of the dihedral principle. This principle was undoubtedly used successfully here; with the planes of rotation of the laterally and longitudinally disposed airscrew at a dihedral angle to one another.

The control secured was apparently complete by making all the lifting propellers variable and reversible in pitch, and by using the two small variable-pitch directional propellers, with axes horizontal, placed on either side of the fuselage.

In order to reverse the pitch of the blades of the main lifting screws a hollow shaft is fixed to the frame, and the end extends upward to a floating bearing which acts as a hub for a hollow shaft. A reversing and adjusting sleeve and levers are adapted to be operated vertically by movement of the shaft mounted within the adjusting sleeve in order to adjust the blade angle. The shaft is vertically operated by means of spiral threads and a spiral-threaded member, the threads being operated by a sprocket to set the pitch of all the propellers' members simultaneously in the same direction, and the threaded member which is operated by a lever for lateral stability by relative variation of the blades of the opposite lifting screws.

Forward motion was apparently secured by tipping the helicopter forward. With the variable pitch of the four airscrews, lateral as well as longitudinal control was secured. The possibility of tipping the helicopter in any sense permits its displacement being effected in any direction.

While no attempts were made to land the helicopter with its engine cut, the design provided for reversing the blades on descent and securing windmill resistance, and also for a reversal to normal position just before reaching the ground.

Damblanc Helicopter. The Damblanc helicopter, while never flown, is an interesting design. The machine is shown in outline in Fig. 12, from which it is seen that the construction was comparatively simple.

Two lifting airscrews were used, driven by cables from two Le Rhone 110 HP. engines. The drive was so arranged that either or both of the two engines could operate both lifting airscrews. An automatic clutch and an elastic shock absorber were embodied in the transmission.

Control was secured by a mechanism for warping the blades (which were built very much like airplane wings), a horizontal stabilizer, and a vertical rudder. Forward speed was to be secured by inclining the airscrews. Apparently for descent the blades were to be put in negative pitch.

The main characteristics were as follows:

Span	49 ft.
Overall length	30.2 ft.
Total area of rotating wings	430.0 sq.ft.
Width of fuselage	3.93 ft.
Area of horizontal stabilizing planes (2)	86.00 sq.ft.
Area of rudder	10.75 "
R.P.M. of blades	160
Total gross weight	2640 lb.
Power of engines	110 at 1300 R.P.M.
Useful weight	Pilot and gasoline for half an hour's flight.

In his paper before the Royal Aeronautical Society*, Damblanc gives some very interesting figures, based on experience

* The Problem of the Helicopter, L. Damblanc, Aeronautical Journal, January, 1921.

and calculation for the weight of his type of airscrew - built in very similar fashion to that of an airplane wing. With a factor of safety of 7, he found that the optimum diameter of a lifting propeller was about 22.6 feet, and that the weight of the propeller per square foot of surface was 1.43 lb.

Damblanc estimated the horizontal speed at 62 M.P.H., and the initial climb at 10 ft. per sec. His machine was wrecked on ground trials, and no further experiments were conducted.

Oehmichen Helicopter.-* This is a very curious machine. While it has completed for the first time in helicopter history, a circular kilometer, has made 450 flights, some at a height of 35 feet, and is perfectly maneuverable and stable, it does not seem possible that so much complexity will persist in the construction of the helicopter. The machine is illustrated in Figs. 13 and 14.

The helicopter's main structure is in the form of a large cross with unequal arms. The longer axis is the longitudinal one and defines the direction of forward flight. At the four terminals of the arms of the cross are placed the lifting propellers. The longitudinal pair of lifting propellers are 25 ft. in diameter and the lateral pair 21 ft. in diameter, all turning at 145 R.P.M. and driven by a system of tubular shafting from a Le Rhone 9-cylinder engine of 120 HP. The engine is placed at the center of the cross, and on the engine shaft is placed a gyroscope (apparently nothing but a flywheel), which has a

*"Les Ailes," February 1, 1923, and "Aviation," August 18, 1923.

maximum peripheral velocity of 425 ft. per sec. This rotating mass is said to insure stability in calm air, and to damp out oscillations in rough air. Two propulsive propellers, of fixed pitch, are belt-driven and placed as shown in Fig. 14. These are of 4.6 ft. diameter and placed about half-way out on the frames which support the lifting propellers. To counteract the torque of the engine and the gyroscope, a propeller with its axis horizontal and athwartship is placed far forward. In addition, five auxiliary propellers, "evolueurs" as Oehmichen terms them, are used. These are variable-pitch propellers of 4.75 ft. diameter, driven from the shafts of the main lifting propellers. It is quite evident that the control about every axis is fully provided for. The landing gear consists of a peculiar system of six footballs at the end of shock-absorbing and pivoted struts. A double skid has been recently introduced into the forward part of the machine. The gross weight of the machine is about 2200 lb., with a load of 6.6 lb. per sq.ft. of blade area.

La Cierva's Autogiro.* La Cierva's Autogiro is a most curious machine, neither a helicopter nor an airplane, but with a windmill operating in a lateral wind providing sustentation. The principles of operation of the windmill have already been described. The machine is illustrated in Fig. 15. The Autogiro weighs about 880 lb. empty, and 1100 lb. loaded. With an 80 HP. engine the maximum speed is 55 M.P.H.; the minimum speed

* Aviation, April 9, 1923.

is 33 M.P.H. The rotational speed of the lifting vane is about 140 R.P.M. The diameter of the vane is 26.2 ft. The vertical component of velocity on a steep glide is said to be surprisingly low. The Autogiro certainly deserves careful consideration.

Conclusion

While predictions in matters regarding the helicopter are rash, it is safe to say that three lines of development are definitely open: (1) The combined helicopter-airplane; (2) the multiple-engined helicopter; and (3) the helicopter with gliding ability by virtue of windmill action of the reversed-pitch airscrews.

The combined helicopter-airplane, of which the Berliner is such an excellent example, is a thoroughly practical proposition. Since descent with engine dead is taken care of by airplane wings, comparatively small airscrews need be provided. This means general compactness of design, high values of V/nD, and ultimately good efficiency in forward flight. Also, since descent is taken care of by gliding planes, the main lifting screws do not need variable pitch, and the mechanism is reduced to a simple speed-reduction and power-transmission problem. Mechanical simplicity is thus assured. This type of craft is not so likely to be very efficient in vertical climb, since it will have a very large wing surface resisting upward motion. The climb of a helicopter-airplane will be more analogous to that of an ordinary airplane. On the glide, it is not to be hoped for that this type will be as efficient as an ordinary airplane. In hovering, more power is likely to be required than in the helicopter proper. The combined helicopter-airplane, while the most readily realized, may be said to depart from the ideal conception of a helicopter, which can rise vertically with ease and descend with engine cut out, either vertically or on a very steep path. It may be a very valuable compromise between the airplane and the helicopter proper.

The multiple-engined helicopter has never been seriously attacked. Damblanc's "Alerion," with its two engines, each capable of driving the two sustaining airscrews, is the nearest approach to such a type. A machine is conceivable with, say, six small independent power units. On descent, reliance could then be placed entirely on the power plant. The airscrews could therefore be of the small dimensions needed for compactness and efficiency in forward flight. Variable pitch for the main lifting screws could be eliminated. The multiple power plant has difficulties and complications of its own, but the type is well worth considering. It should give us the closest approach to the ideal helicopter, and possibility of good speed as well as climb. The aerodynamic problems would be somewhat minimized.

The third type is the one which has received most attention hitherto, and such designs as those of De Bothezat and Damblanc show that it is practically realizable. It should be possible with this type to secure control, stability, excellent vertical climb, hovering flight, moderate forward speed, and, provided suitable windmill action can be secured, a steep, safe descent with engine out of commission. It will be more complex than the first two types, with variable-pitch propellers as an absolute necessity. It will approximate to the ideal helicopter more closely than the combined helicopter-airplane, less closely than the multiple-engined type. Besides its inevitable complexity, it is never likely to achieve great forward speed, and its load-carrying capacities are likely to prove disappointing. In spite of these difficulties, it may be developed because it does not involve the disadvantages of multiple engines and because it does approximate to the ideal helicopter. Some plausible calculations by the author indicate that with a 200 HP. engine a helicopter of this type could be built to weigh about 3000 lb. carrying a man and a couple of hours' fuel load, be equipped with two main lifting airscrews of 30 ft. diameter each, climb vertically at 500-600 ft. per min., have a forward speed of 60 M.P.H., and glide down safely with engine dead on a path of 30 deg. to the horizontal at an angle of incidence of 30 deg. so that craft would maintain a horizontal position on the glide, and come to rest very quickly after touching the ground.

There is no doubt that any of the three types discussed above can be realized in practical form, and that the general characteristics of the helicopter are already well understood.

Given more fundamental work in the wind tunnel and financial support, aeronautical engineers will readily produce a workmanlike craft.

It is also suggested that aerodynamic research be conducted before the construction of full-sized machines is undertaken. Langley and the Wrights undertook such investigation before building their flying machines. Surely the wind tunnel should now be called upon for investigating stability, windmill action in gliding descent, conversion of a lifting airscrew into a windmill, and efficiency of the lifting airscrew in forward flight.

The helicopter is not likely to equal the airplane in speed or in carrying capacity. Owing to the large airscrew diameters required, it is not likely to be so compact or maneuverable. With engine dead, however, it should be able to land in worse and more restricted terrain, and that is an important point from the safety aspect. But the airplane has only one mechanical contrivance of any complexity: the engine. The helicopter with multiple-engine power plant will have reduction gearing (10 to 1, or thereabouts) to contend with, and a complicated system of control. The single-engined helicopter will have to include a variable-pitch mechanism in addition. The airplane engineer builds a structure which glides through the air, but with its parts stationary relative to one another. In the helicopter weight limitations and the flexibility of a light, huge device will make all the mechanical problems of transmission, etc., particularly difficult, and such difficulties militate against safety.

The future of the helicopter, unless it undergoes radical development, therefore lies not in competition with the airplane, but in its ability to perform certain functions which the airplane cannot undertake.

Before the complete development of a new mechanism of transportation, it is impossible to predict all the uses to which it may be put. It is doubtful whether the Wrights foresaw the application of the airplane to fighting the boll weevil, or making air surveys for laying down power-transmission lines. By analogy, the helicopter, once it has been developed, may be utilized in ways quite unsuspected by us at present. There is no lack of plausible suggestions for its utilization. In military use for observation purposes, to replace kite balloons or over areas where extremely accurate information is required; for securing communication between army units which cannot maintain airplane contact owing to topography; for accurate bombing of either land or sea objectives; for use in connection with naval vessels not supported by aircraft carriers. Enthusiastic supporters of the helicopter go so far as to see it landing on roofs, bringing rapid communication to the very heart of cities and helping to relieve traffic congestion - although airplanes with landing platforms may more readily achieve this.

At any rate, the helicopter is within measurable distance of achievement, and is worthy of serious consideration.

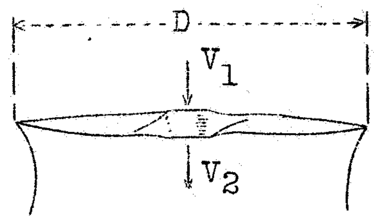


Fig.1 Diagram to illustrate the Froude momentum theory, as applied to a lifting airscrew.

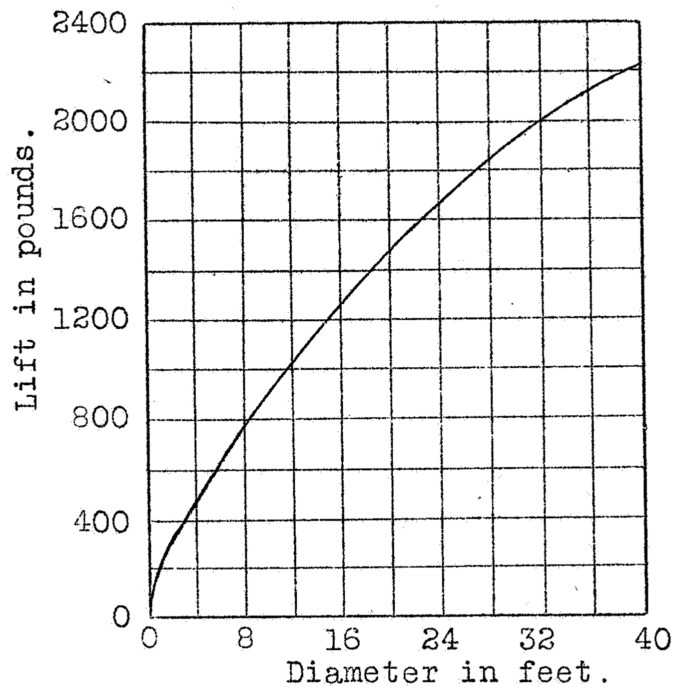


Fig.2 Lift in pounds plotted against diameter for Durand propeller No.44 with constant 100 HP.

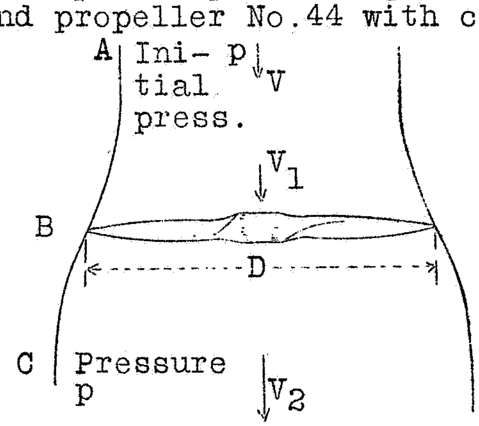
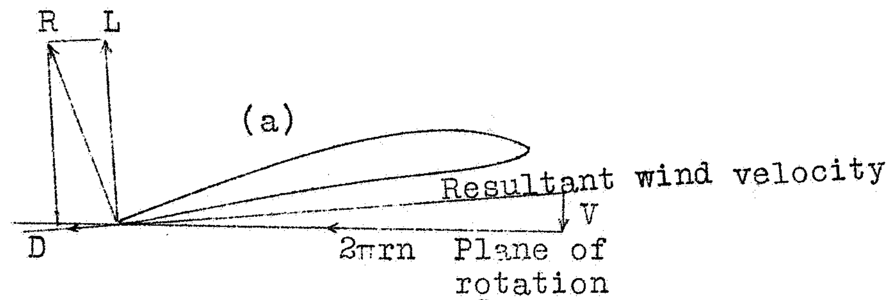


Fig.3
Diagram to illustrate the Froude momentum theory as applied to an airbrake.



(b) Air forces on an element of a normal airscrew in vertical descent; R exercises a torque producing a negative rotation; rear edge meets the resultant wind.

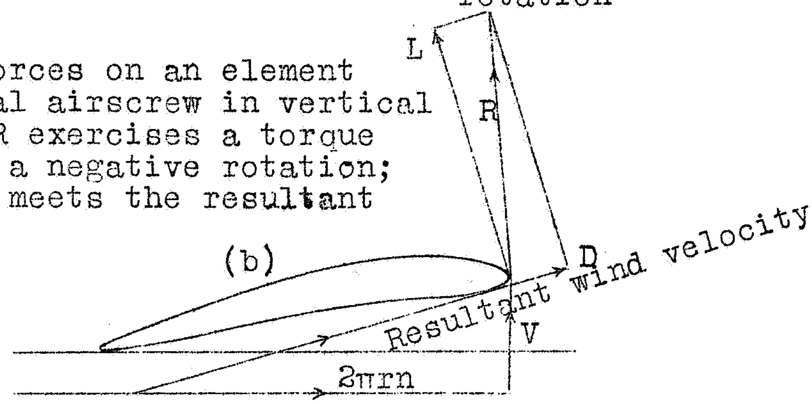


Fig.4 Action of blade element of a normal airscrew on vertical descent.
(a) Air forces on an element of a normal airscrew in vertical ascent; positive direction of rotation; power supplied.

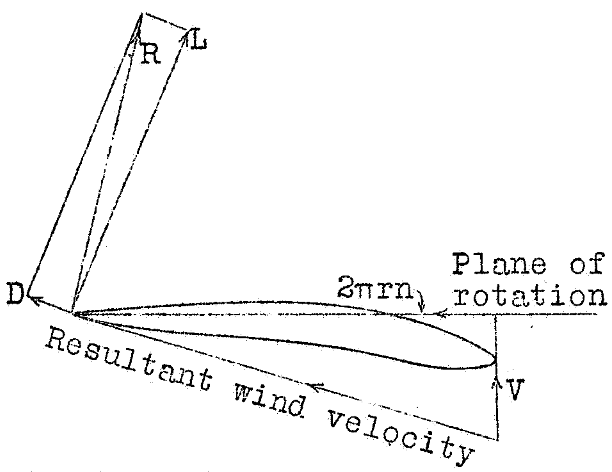


Fig.5 Action of blade element of a windmill brake on vertical descent.

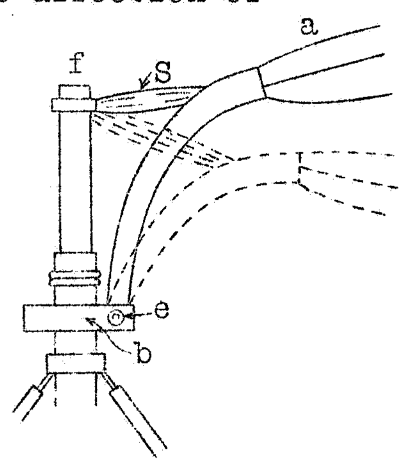


Fig.6 Principle of La Cierva's autogiro.
(The wings are fixed to a piece b, by means of hinges e, so that they are free to move as shown in the diagram. The piece b turns freely about the axis f. S are elastic shock absorbers limiting the downward motion of the wings.)

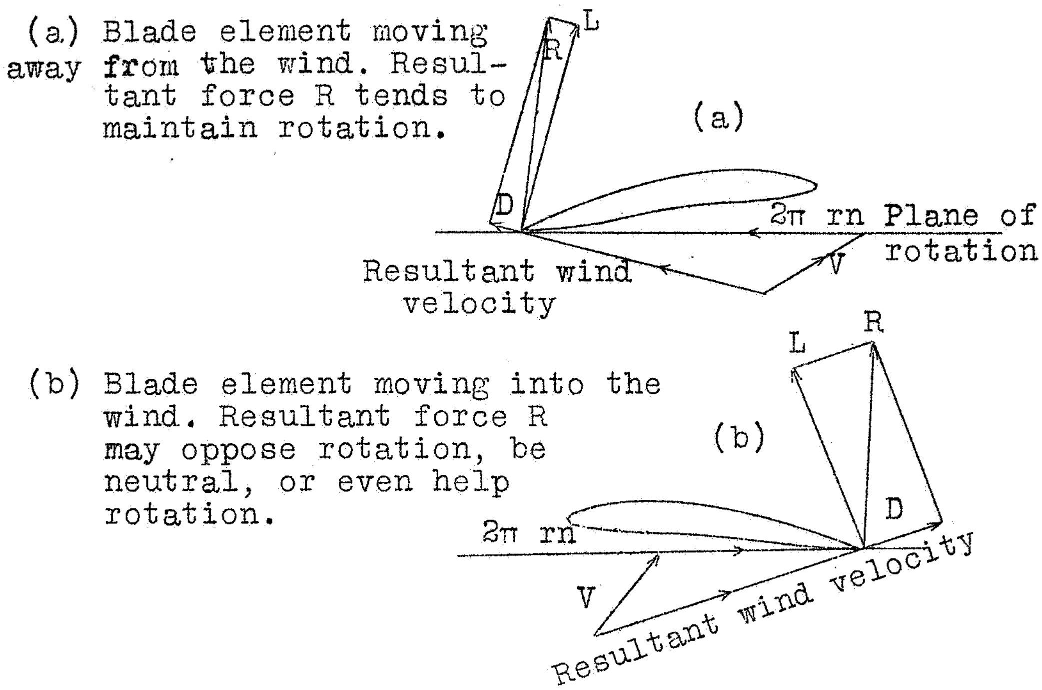


Fig.7 Diagrams to illustrate the action of blade elements of a windmill in side wind.

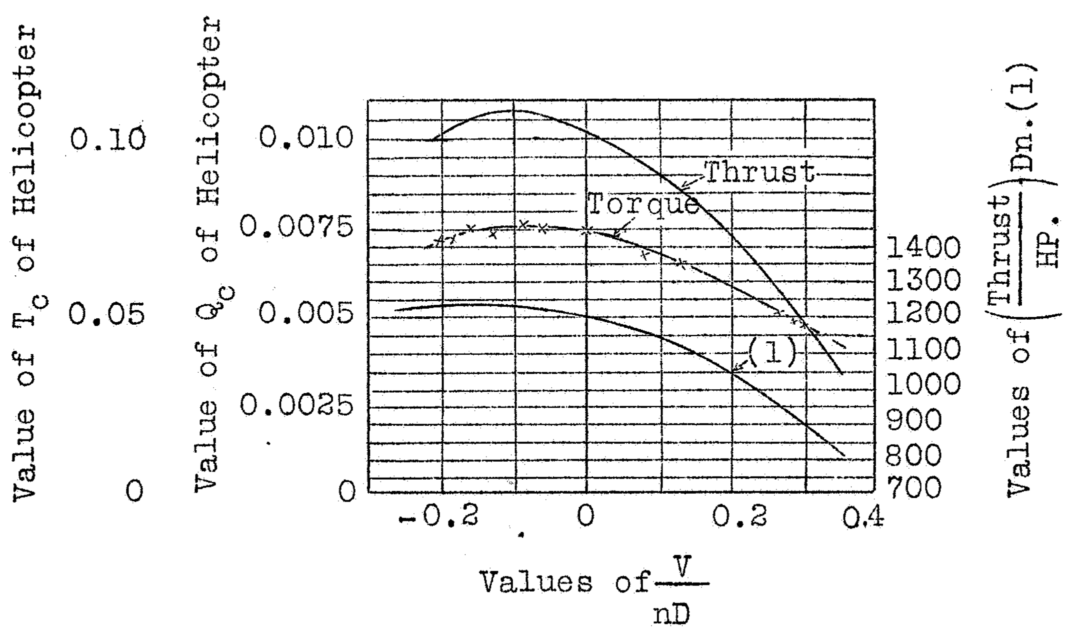


Fig.8 Characteristics of a Helicopter airscrew at varying values of V/nD

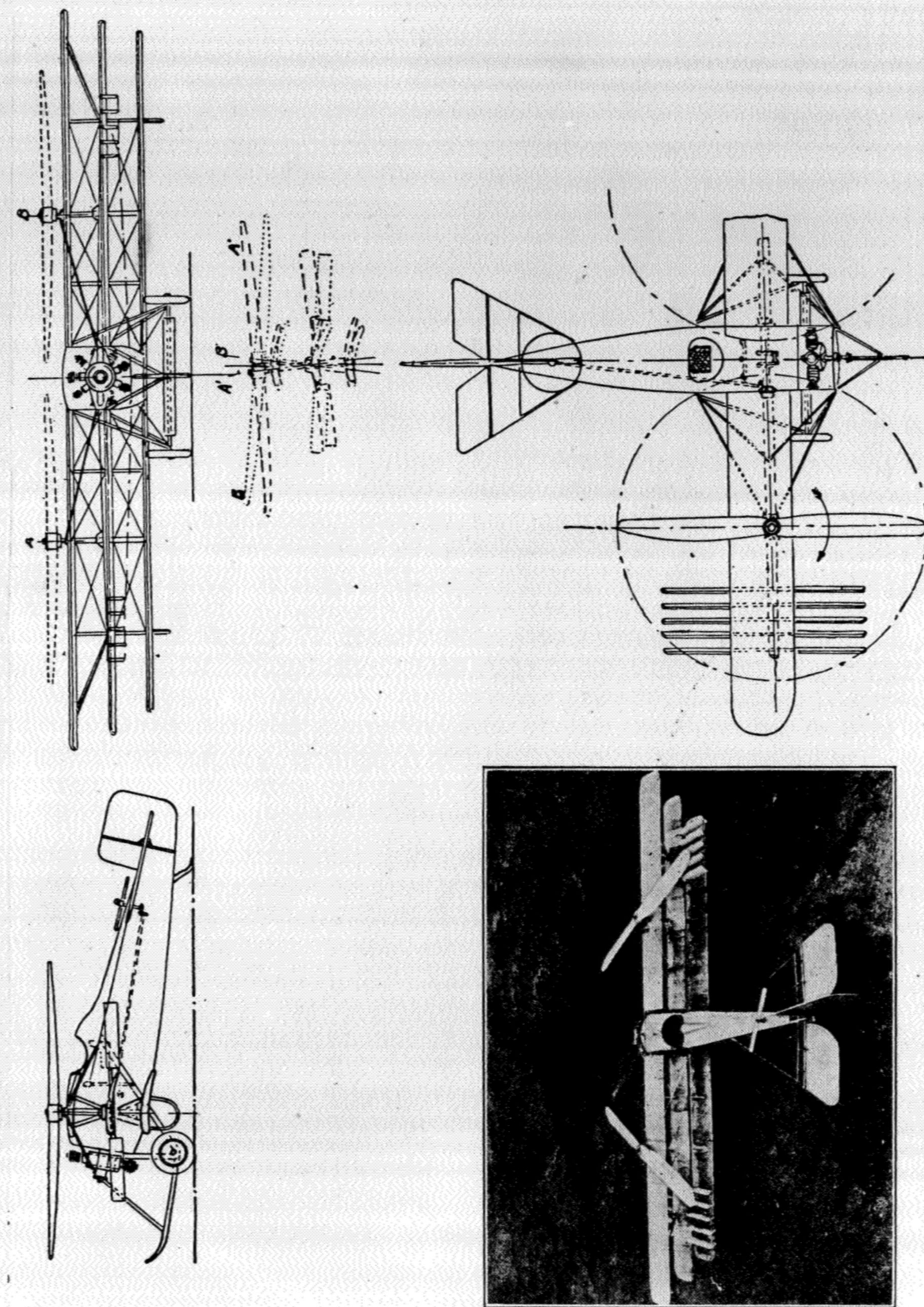


Fig.9 Plan,elevation and view of a recent form of the Berliner Helicopter

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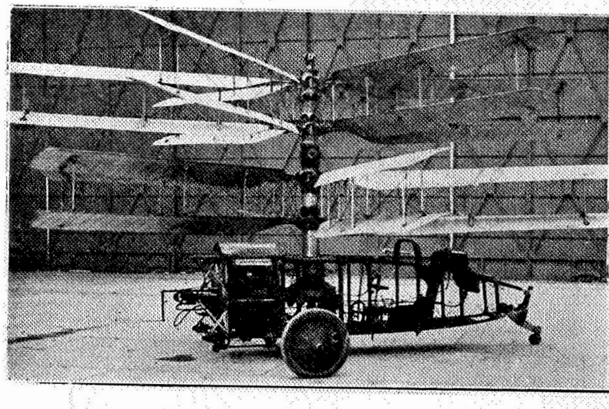


Fig.10 Pescara Helicopter

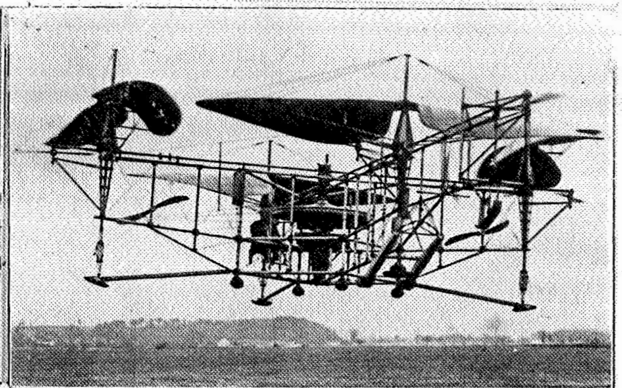


Fig.13 Oehimichen Helicopter

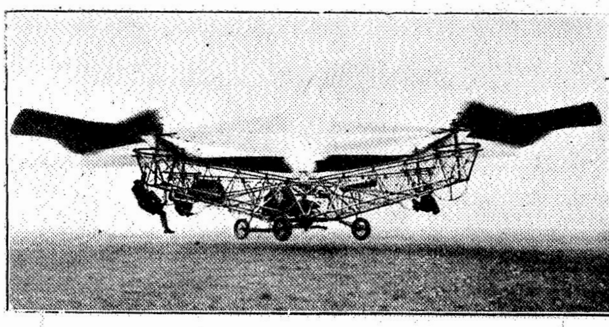


Fig.11 De Bothezat Helicopter

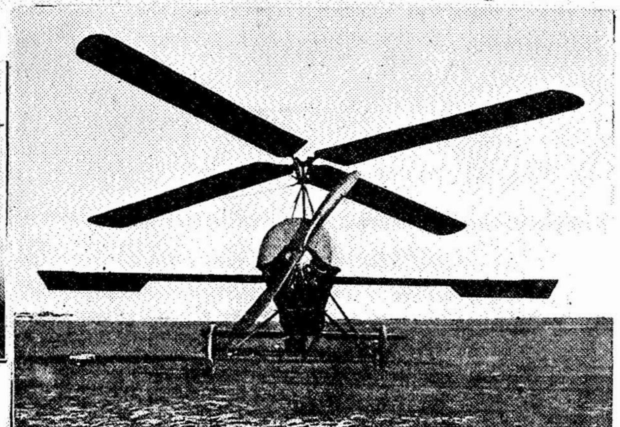


Fig.15 La Cierva's Autogiro

Fig.16 Karman Helicopter without turrent.

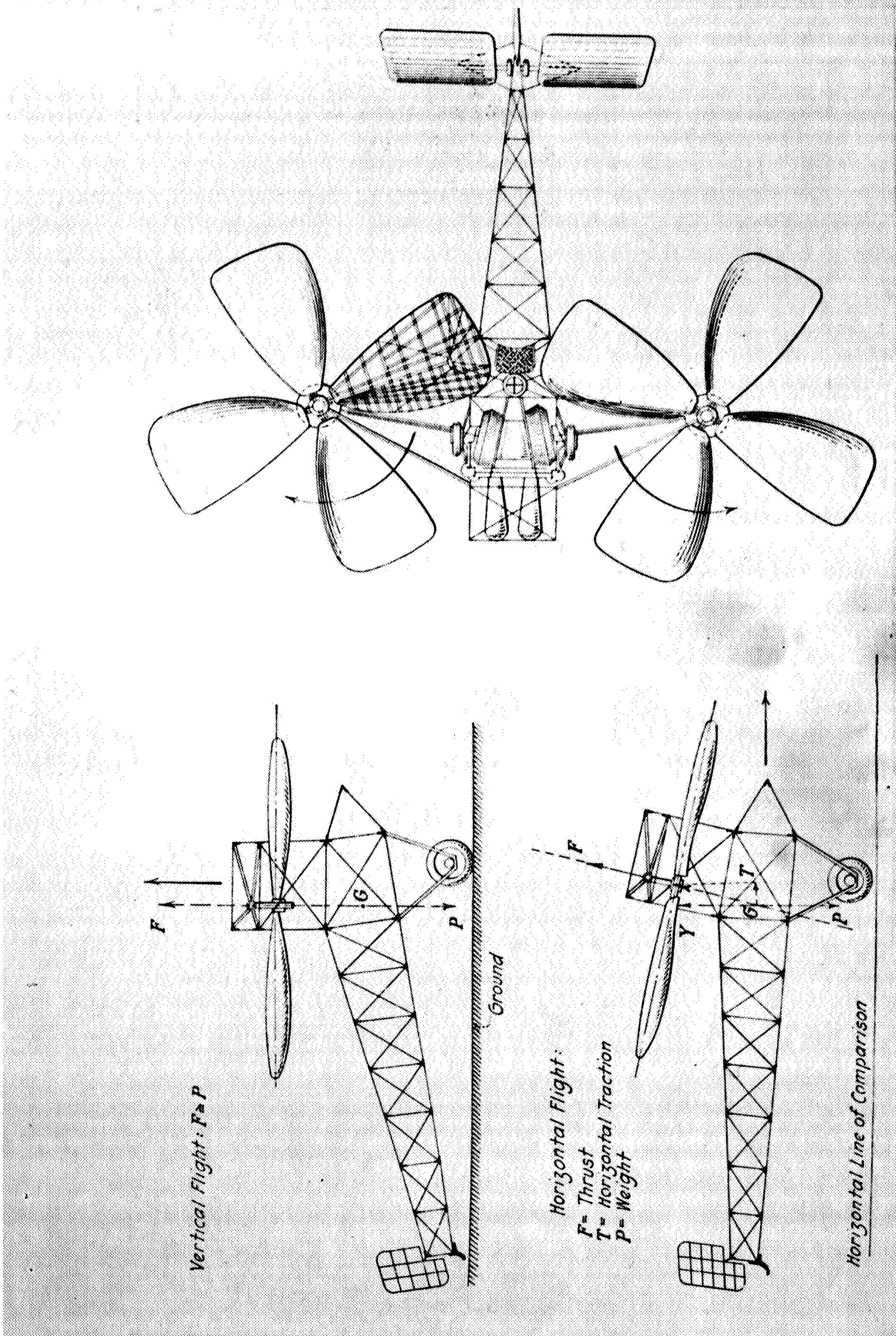


Fig.12 Damblanc Helicopter

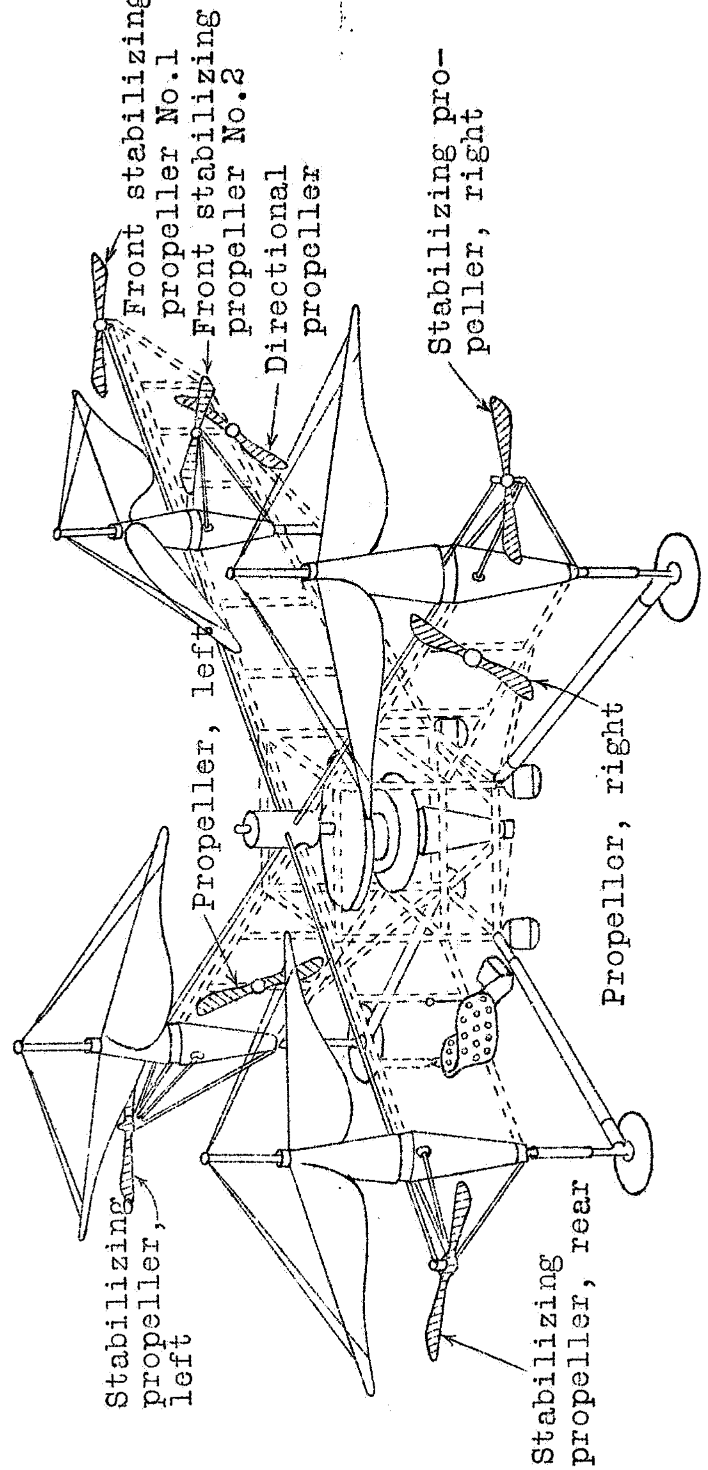
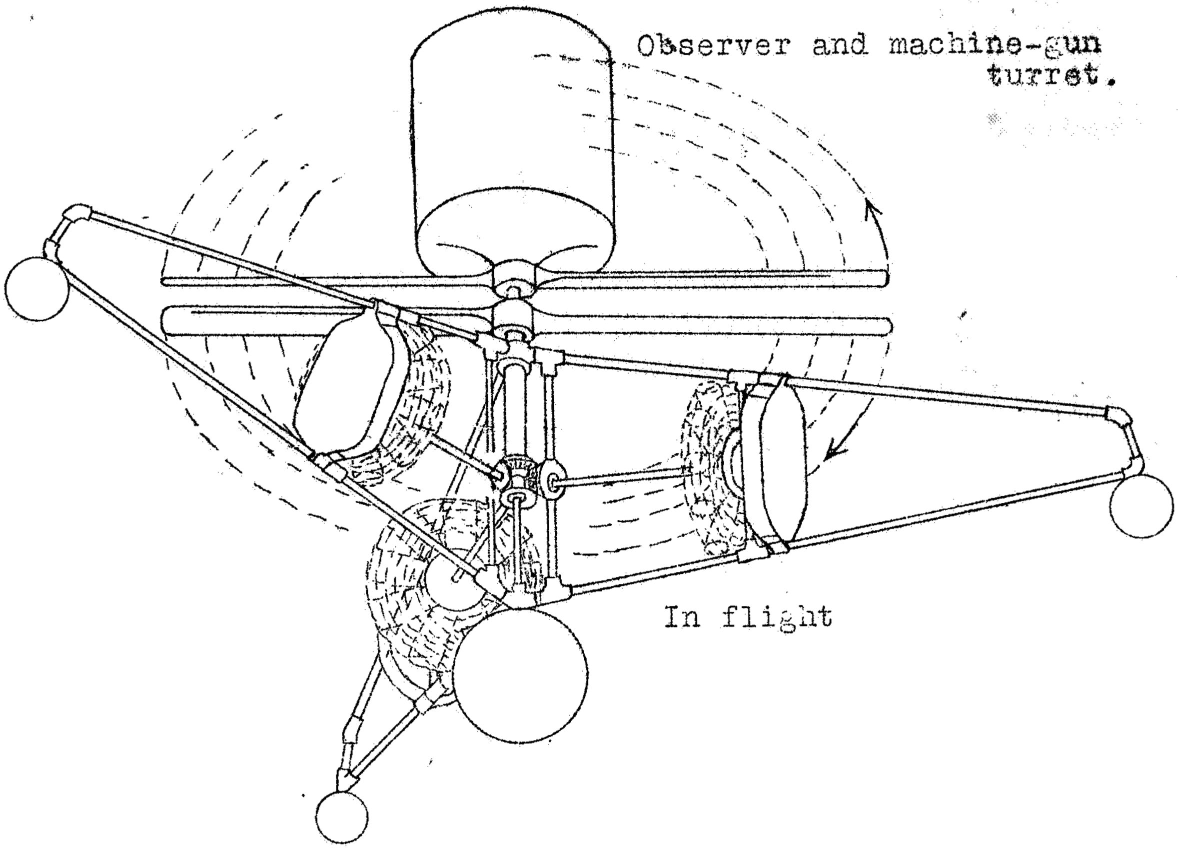


Fig.14 Diagram of the Oehmichen Helicopter.



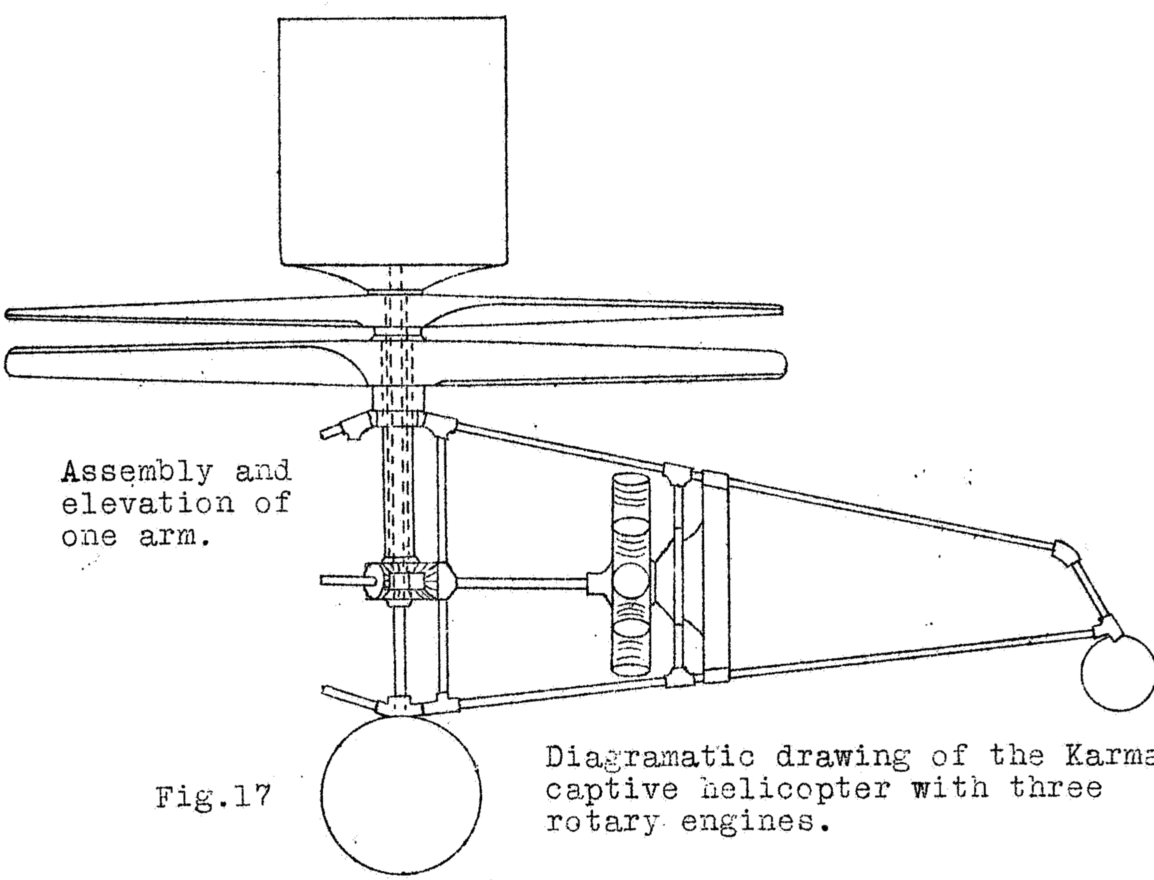


Fig.17 Diagramatic drawing of the Karman captive helicopter with three rotary engines.